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Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective

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HIGHLIGHTS

- Demand-side flexibility is integrated into an energy systems model (ESM)
- Household appliances and electric cars can provide significant load management.
- By 2050, the peak load can be significantly reduced, with large cost savings.
- ESMs should consider demand-side flexibility as a key mitigation option.

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ABSTRACT

Demand-side flexibility from smart appliances and passenger electric vehicles has been increasingly regarded in recent years as an effective measure to reduce peak loads and to aid system balancing. While numerous studies have been undertaken to investigate the benefits of demand-side flexibility, most have either focused only on the power sector or provided a snapshot for a future year or day. The influence of interactions between sectors in the long-term under energy transition pathways has therefore been under explored. This paper presents a novel modelling approach in a whole energy systems model, UK TIMES, to investigate the benefits of demand-side flexibility from smart appliances and passenger electric vehicles, including the reduction in the costs of moving to a low carbon economy. This analysis shows that demand-side control increases system flexibility, enabling the integration of high levels of low carbon power, such as nuclear and wind, whilst reducing the requirements for storage. By 2050, the peak load is reduced by around 7 GW (9%), and cumulatively about 30.9 billion GBP saved with the help of this demand-side flexibility. This approach could be integrated into other energy systems models to improve the representation of this important flexibility mechanism.

1. Introduction

The UK set an ambitious legally-binding target to reduce greenhouse gases (GHGs) emissions to at least 80% below 1990 levels by 2050 in the UK Climate Change Act [1]. A key option to decarbonise the energy system is the increased electrification of end-use sectors, based on a supply of low carbon electricity. According to estimates [2,3] the level of electricity consumption in 2050 through this push for more electrification could be 50–135% higher than the current level. This increase could impose a serious challenge to delivering sufficient electricity supply while at the same time reducing total GHG emissions from the power sector. Low carbon technologies, such as nuclear, renewable energy and thermal power plants with CCS, therefore need to be deployed at scale. In view of the recent cost reductions for renewables, such as wind turbines and solar PV [4], the system may see increasingly strong deployment of these intermittent generation sources, as the Government also seeks to provide affordable electricity to avoid cost increases to households and other economic sectors. The capacity of such variable renewable energy (VRE) sources could increase to 89 GW, providing about 46% of total electricity generation by 2050 [5]. However, high shares of renewable energy pose significant challenges to a stable electricity system due to their intermittent nature. High wind speed during one period could lead to a surplus of electricity; low wind speed at another period in time could cause a supply deficit.

At the same time, increasing electrification in end-use sectors could lead to higher fluctuations (difference between peak and average demand) across the daily demand profile. This increases the challenge of moving from dispatchable generation to more intermittent or less responsive generation, such as nuclear power. While dispatchable plants, such as gas-fired power plants, and storage systems may need to be

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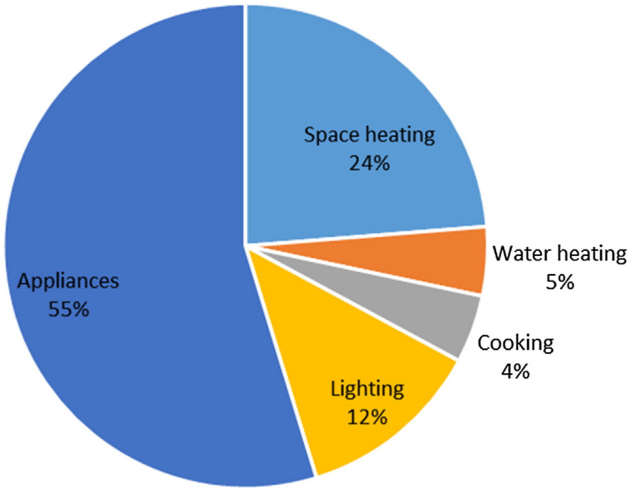

Fig. 1. Electricity consumption by type in the domestic sector in 2016.

deployed to balance electricity supply and demand across short time periods to cope with intermittency, such technologies may be either carbon-intensive or costly.

Demand-side flexibility via demand-side response (DSR) in the end-use sectors is the other promising mechanism to balance the electricity system. For example, with smart controlled appliances in the domestic sector, the electricity load can be shifted or shedded within a short period of time to match the variation in the supply profile of VRE [6–8] or to even out the demand profile to allow for nuclear power on the same system.

In 2016, the UK residential sector consumed 108 TWh, or about 36% of the total electricity demand, the largest share of all end-use sectors [9]. Electricity is consumed to provide a range of energy services including space heating, water heating, cooking, lighting and appliances, as shown in Fig. 1. This electricity consumption could increase dramatically in the future if residential heating were to be decarbonised through electrification using heat pumps (HPs) and electric heaters. Under some projections, the installation of HPs could increase to 16.7 million units [5], or be installed in approximately 49% of households. Similarly, electrification could play a strong role in the transport sector [3], particularly for powering cars and other light duty vehicles, despite currently accounting for only 0.04% (0.13 TWh) of total electricity demand [9].

The projected high electrification level of the residential and transport sectors provides an unprecedented opportunity to significantly increase demand-side flexibility via smart control mechanisms, in order to accommodate low carbon electricity into the future UK energy system, and in doing so reduce energy system costs. In order to exploit these benefits, the UK government plans to roll-out smart meters to every household in the UK by 2020 [10]. The Smart Systems and Flexibility Plan has also been proposed to deliver a smarter and flexible energy system by removing barriers to smart technologies, enabling smart homes and businesses, and making markets work for flexibility [11].

In recent years, numerous studies have been carried out to assess the value of demand-side flexibility. However, most of the studies only consider the impacts on a specific or limited number of sectors, with only partial consideration of path dependency issues or sectoral interactions. No study has yet incorporated demand-side flexibility in a whole energy systems model, where all sectors supplying and consuming different energy types across the system are included, as described in this paper. To date, the complexity of such models has been a barrier to the integration of the dynamics of demand-side flexibility.

To help address this gap, this study aims to develop a novel modelling framework in a whole energy systems model, UK TIMES (UKTM), to assess demand-side flexibility benefits across a long-term energy transition. Despite the temporal resolution of such models being relatively coarse compared to power sector-only models, the variations in demand load can still be captured to a certain level [12,13]. Therefore, this approach has the advantage of capturing dynamics across and between sectors, and can endogenously estimate the techno-economic benefits of demand-side flexibility.

The proposed approach has been applied to specifically explore the potential of demand-flexibility across electricity-using household appliances and passenger EVs, given the prospective increase in electrification. Firstly, the impact of demand-side flexibility on the system-wide electricity supply and consumption is investigated. Secondly, the specific issues related to the deployment of such flexibility options in the residential and transport sectors are then considered. Finally, the impacts on GHG emissions and total energy system costs are estimated.

The contributions of this study are thus twofold:

- Demand-side flexibility from smart controlled appliances and passenger EVs are incorporated in the TIMES framework to determine the optimal scheduling operation.
- The influence of demand-side flexibility of smart controlled appliances and passenger EVs on the whole energy systems is assessed.

We structure the paper as follows; Section 2 provides a review of the relevant literature on how demand-side flexibility has been modelled previously, and the insights provided. Section 3 describes the UKTM model, and the new approach to modelling demand-side flexibility. Section 4 presents the results of the analyses that shows the impacts of introducing demand-side flexibility for smart appliances and passenger EVs into the model. Finally, Section 5 draws out the main conclusions from the study.

2. Literature review

DSR is a means of reducing peak loads to avoid the procurement of extra electricity from conventional power plants and the resulting increased cost of electricity generation. However, in recent year, the concept of DSR has been expanded also to enable the matching of demand load profiles to electricity generation profiles as increasing intermittent renewable energy flows into the electricity grid. Some regulatory examples include reducing or interrupting consumption temporarily, shifting consumption to other time periods, and temporarily utilising onsite standalone generation [14].

DSR can participate in the wholesale markets in two ways [15]: price-based and incentive-based DR schemes. In a price-based scheme, consumers are offered time-varying rates for different time periods. Some example schemes include time of use (ToU), critical-peak price (CPP) and real-time price (RTP). In incentive-based schemes, consumers are encouraged to reduce their energy consumption upon request or according to a contractual agreement between the consumer and the utility company. Utility companies can be granted a certain level of authority to schedule or reduce energy consumption to save electricity generation costs. Interruptible tariffs, demand-bidding programs and direct-load controls (DLCs) all belong to this type of scheme. Almost all DSR programs require consumers' active participation and can cause disruption to daily routines, and therefore the impact of such measures on consumer behaviour is highly uncertain [16]. Therefore, this study only considers the DLC type of scheme as this minimises the interruptions to consumers and requires only passive compliance from consumers.

There have been numerous studies assessing the impact of demand-side flexibility via DSR on energy systems. Some of the recent studies have been reviewed here to identify the research gap, and are categorised into national-scale, sub-national-scale and whole energy systems model-related studies. Studies using whole energy system models are limited and directly relate to this study; therefore, they are